

## CONSTRAINING THE ORIGIN OF IMPACT CRATERS ON AL FOILS FROM THE STARDUST INTERSTELLAR DUST COLLECTOR.

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**Introduction:** Preliminary examination (PE) of the aerogel tiles and Al foils from the Stardust Interstellar Dust Collector has revealed multiple impact features. Some are most likely due to primary impacts of interstellar dust (ISD) grains, and others are associated with secondary impacts of spacecraft debris, and possibly primary impacts of interplanetary dust particles (IDPs) [1, 2]. The current focus of the PE effort is on constraining the origin of the individual impact features so that definitive results from the first direct laboratory analysis of contemporary ISD can be reported. Because crater morphology depends on impacting particle shape and composition, in addition to the angle and direction of impact, unique particle trajectories are not easily determined. However, elemental analysis of the crater residues can distinguish real cosmic dust from the spacecraft debris, due to the low cosmic abundance of many of the elements in the spacecraft materials. We present here results from the elemental analysis of 24 craters and discuss the possible origins of 4 that are identified as candidate ISD impacts.

**Methods:** Members of the ISPE team located craters in the Al foils through a combination of automated scanning electron microscope imaging, automated image analysis, and manual inspection of images [2]. Elemental analysis of crater residues was performed with Auger electron spectroscopy (AES) at Washington University, conventional energy dispersive X-ray (EDX) spectroscopy at the MPI for Chemistry, and EDX with a specialized annular-quadrant silicon drift-detector at Sandia National Laboratory. Ultra-thin sections of craters were obtained by focused ion beam lift-out, from those craters not immediately identified from AES or EDX as debris from the spacecraft solar cell array. The sections were subsequently analyzed with a scanning transmission electron microscope (STEM) at the Naval Research Laboratory.

**Results:** Crater identification is complete for 9 foils, with a total area of  $3.5 \text{ cm}^2$ ,  $\sim 2.2\%$  of the exposed

foil collection surface. The sizes of the identified craters, calculated as the equivalent diameter, range from  $0.2 \text{ }\mu\text{m}$  to  $1.6 \text{ }\mu\text{m}$ , however those identified by composition as cosmic in origin, i.e., ISD candidates, cluster at the low end of the size distribution, ranging from  $0.28 \text{ }\mu\text{m}$  to  $0.46 \text{ }\mu\text{m}$  (Table 1).

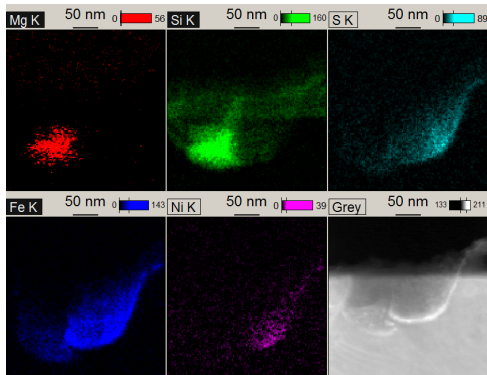
STEM-based EDX mapping (e.g., Fig. 1) of all 4 cosmic craters indicates that the residues are heterogeneous in composition, with distinct silicate-rich and sulfide rich regions. Two of the 4 craters have complex cross-section profiles (Fig. 1, lower right and Fig. 2) rather than symmetric bowl shapes. In contrast, the secondary impacts have homogenous residue compositions and simple cross-section profile shapes.

**Discussion:** The majority of the observed craters are secondary impacts of fragments of the (Ce, Zn, Ti, K, Na)-doped borosilicate solar cell cover glass and/or the associated 150-nm thick MgF anti-reflection coating. Four craters contained either no measureable residue ( $0.35$  and  $0.46 \text{ }\mu\text{m}$ ) or only Fe that appeared to be indigenous to the foil ( $1.1$  and  $1.2 \text{ }\mu\text{m}$ ). These appear to be pits or defects in the foils rather than true impact craters. In one of these ( $0.84 \text{ }\mu\text{m}$  crater), a cover glass fragment impacted on an Fe,Ni-rich impurity in the foil, so that the residue appeared to be cosmic in origin, until the cross-section STEM imaging revealed the majority of the Fe, Ni to be beneath the crater bottom. No mixed residues with both cover glass and cosmic dust components were observed.

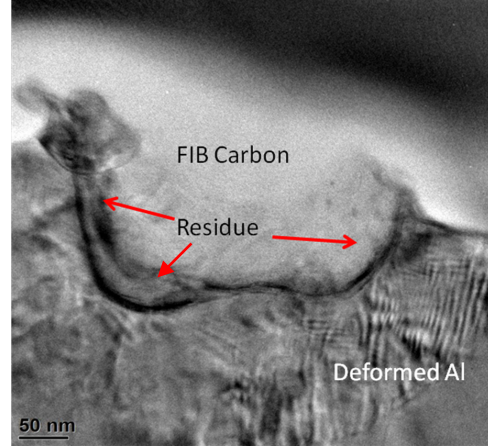
For the 4 cosmic dust craters, the depth/diameter-ratios and retained residue thickness, compared to those obtained in laboratory experiments, model calculations, and Stardust cometary crater studies, allow us to infer an impact velocity of  $< 10 \text{ km/s}$ , probably closer to  $5 \text{ km/s}$  [3]. This is in agreement with the capture velocity of 3 of the 4 ISD candidates found in the aerogel, and indicates a  $\beta$  (ratio of solar radiation pressure to solar gravity) value of  $\sim 1.5$  [4]. Given this impact velocity and an assumed particle density of  $2.2 \text{ g/cm}^3$ , the dust grain diameter can be estimated to

**Table 1. Elemental Analysis of Residues.** Results in bold are from craters identified as cosmic in origin. Elements listed in italics are tentative identifications. Al, C, and O were detected in all analyses in addition to the elements listed. Empty brackets denote no additional elements detected.

Diameter (μm)	Elements Detected (AES)<SEM-EDX>[AQ-EDX]{STEM-EDX}
0.24	(B,Mg,Si,Ti,Ce)
<b>0.28</b>	<Mg,Si,Fe>{Mg,Si,S,Fe}
0.29	(F,Mg,Si)
0.29	[] {Mg,Si,Ti,Fe Ce}
0.35	(Mg,Si)
0.35	{ }
<b>0.37</b>	(Mg,Si,Fe){Mg,Si,S,Fe,Ca,Cr}
<b>0.39</b>	(Mg,Si,Fe){Mg,Si,S,Fe,Ni}
0.44	<Si, Ce, Zn,Na>
0.45	[Si]{Si,Na,Ti,Zn,Ce}
<b>0.46</b>	(Si,Fe){Mg,Si,S,Fe,Ni,Ca,Cr}
0.46	{ }
0.56	(B,F,Mg,Si,Ti,Ce)
0.58	<Si,Fe>
0.61	(Mg,Si)
0.63	(B,Si,Ce,Mg)
0.65	(Mg,Si)
0.66	(Si)
0.74	<F,Mg,Si,Na,Zn,Ce>
0.84	<Si,Fe,Ni>{Si,Ti,Fe,Ni-impurity}
1.0	(Si,Na,Ce,Zn){Mg,Si,K,Ti,Fe,Zn,Ce}
1.1	[] {Fe impurity?}
1.2	() {Fe impurity?}
1.6	[Si,Ce,Zn,Na]{Mg,Si,K,Fe,Ti,Zn,Ce}



**Figure 1. STEM-EDX net count maps and dark-field image of the cross-section of the 0.39 μm crater.**



**Figure 2. Bright-field TEM image of a 0.37 μm crater due to the impact of a cosmic dust grain.**

be  $\sim 2/3$  of the crater diameter, i.e., between 0.2 μm to 0.3 μm, with a mass of  $\sim 10^{-17}$  kg. If the actual particle density is lower, as could be expected for aggregates, the particle size could be slightly higher, up to  $\sim 0.4$  μm for the largest, but the mass would be unchanged.

Possible origins of these cosmic particles include that they are interstellar grains, primary IDPs, or secondary IDPs that collided first with the solar cell array. The lack of any mixing with solar cell residue, or craters from particles larger than  $\sim 0.3$  μm, argues against secondary IDP fragments [4]. The inferred  $\beta$  value indicates that despite the small mass of the particles, they could still originate from interstellar space and not be deflected by solar radiation pressure from reaching the inner solar system. At this particle size, the local particle flux can be enhanced or reduced due to Lorentz interactions with the interplanetary magnetic field. Thus, the agreement of the overall particle flux ( $\sim 10^4/\text{m}^2$ ) to within an order of magnitude of the expected flux ( $< 1.5 \times 10^3/\text{m}^2$ ) in the sub-μm size range, inferred from Ulysses measurements, is well within the uncertainties. The lack of detection of particles in the dominant size of the Ulysses data [5],  $\sim 0.6$  μm diameter, is also consistent with the total foil area imaged and the predicted flux. Thus, an interstellar origin for these particles is plausible, although an interplanetary origin has not been ruled out.

**References:** [1] Westphal A. J. et al. (2011) *LPS XLII*, Abstract #2083. [2] Stroud R.M. et al. (2011) *74<sup>th</sup> MetSoc* Abstract #5118. [3] Price M. C. et al. (2010) *MAPS* 45(9), 1409-14-28. [4] Westphal A. J. et al. (2012) *LPS XLIII*, this volume. [5] Landgraf M. et al. (2003) *JGR* 108, LIS 5-1.

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